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RESEARCH MEMORANDUM

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SUMMARY OF AVAILABLE DATA RELATING TO REYNOLDS NUMBER EFFECTS ON THE MAXIMUM LIFT COEFFICIENTS OF SWEPT-BACK WINGS

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY OF AVAILABLE DATA RELATING TO REYNOLDS NUMBER EFFECTS ON THE MAXIMUM LIFT COEFFICIENTS OF SWEPT-BACK WINGS

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SUMMARY

The available foreign and American data relating to Reynolds number effects on the maximum lift coefficients of swept-back wings are summarized and discussed.

The data show that at low Reynolds numbers (below about 2.0×10^6) higher maximum lift coefficients were measured in most cases for moderately swept-back wings than for unswept wings of similar plan form; at high Reynolds numbers, however, increasing sweepback resulted in decreasing maximum lift coefficients. A smaller rate of increase of the maximum lift coefficient with Reynolds number was measured for the swept-back wings than for similar unswept wings in the critical range of Reynolds number. Increasing the Reynolds number resulted in decreases in the maximum lift coefficients of the two wings of approximately triangular plan form that were investigated.

INTRODUCTION

It is commonly accepted that, in the range of Reynolds number corresponding to the landing and take-off speeds of most aircraft, the maximum lift, the stall progression, and the low-speed stability and control characteristics of highly swept-back wings are inferior to otherwise similar unswept wings. The recent trend towards the use of highly swept-back wings for high-speed aircraft has emphasized the inherently poor low-speed characteristics of these wings. At the present time, however, there are little systematic experimental test data existent relative to the detail characteristics of swept-back wings when operating in the high-lift region. Furthermore, most of the experimental data available have been obtained at very low values of Reynolds numbers. The maximum lift coefficient, in particular, is dependent to a great extent on the behavior of the boundary layer over the wing surface, which in turn is dependent on the value of the Reynolds number (reference 1). For the swept wing, premature tip-stalling tendencies may influence the value of the usable maximum lift coefficient when consideration is given to flying qualities in the region of maximum lift.

In order to assist the designer in evaluating the results of tests made at low Reynolds numbers until sufficient data at high Reynolds numbers become available, a survey has been made of the available foreign and American data relating to Reynolds number effects on the maximum lift coefficients of swept-back wings. The data, which represent the accumulation of results from a large number of wind tunnels, are presented in the present paper, along with some analysis. Because of the lack of systematic test data, this survey is intended mainly to show trends characteristic of the particular wing plan forms discussed in the present text and figures. In cases where similar wing plan forms were tested in different wind tunnels, it is possible that small differences in the section contours of the wing existed because of different manufacturing tolerances which may have influenced the maximum lift values of these wings.

COEFFICIENTS AND SYMBOLS

$C_{L_{max}}$ maximum lift coefficient

Λ angle of sweepback of wing leading edge, degrees

R_{eff} effective Reynolds number $\left(\frac{\rho V c_m}{\mu} \times \tau\right)$

V free-stream velocity

ρ mass density of air

μ coefficient of viscosity of air

τ turbulence factor of wind tunnel as determined from sphere tests

c wing chord measured parallel to plane of symmetry

c_m mean geometric chord (S/b)

c_t wing tip chord

c_r wing root chord

c_s leading-edge-slat chord

c_a aileron chord

b wing span measured perpendicular to plane of symmetry

b_a aileron span

A wing aspect ratio (b^2/S)

S wing area

δ_f landing-flap deflection about hinge axis, degrees

δ_a aileron deflection about hinge axis, degrees; subscript R and L denote right and left aileron, respectively

PRESENTATION OF DATA

Curves showing the variations of maximum lift coefficient with effective Reynolds number for several swept wings of various taper ratios and aspect ratios are given in figures 1 to 3. Data for similar unswept wings are included on the figures wherever possible for purposes of comparison. The effects of changes of wing-tip thickness and of wing camber on the variation of maximum lift coefficient with Reynolds number for one swept-back wing is given in figure 4. The results of separate investigations, to determine the effects of sweepback on maximum lift, each made at a constant value of Reynolds number, are given in figure 5. These results include tests made at low, moderate, and high Reynolds numbers. In a few instances, data were available to show the effects of various landing aids and of wing-fuselage interference on the variations of maximum lift coefficient with Reynolds number; these results are shown in figures 6 and 7, respectively. For convenience, the plan form of the model tested, the most important geometric parameters, and the source of the data are given on each figure. The airfoil sections noted in the figures are all NACA profiles, taken parallel to the plane of symmetry of the wing except where noted. All the data were obtained at Mach numbers below about 0.25. In the few cases in which data were obtained at Mach numbers above 0.2 (data for wings 3,4,5,6, and 12 at high Reynolds numbers), it is possible that the values of the maximum lift coefficients were influenced by Mach number effects. These effects will probably be most pronounced for the wings which employ airfoil sections that exhibit high leading-edge pressures.

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In order to provide a basis for comparison, effective Reynolds numbers based on a turbulence factor for each tunnel have been used for all the tests. The turbulence factor is defined, according to reference 14, as the ratio of the critical Reynolds number of a sphere in a nonturbulent air stream to the critical Reynolds number in a wind tunnel. The turbulence factor for each wind tunnel from which data for the present paper have been obtained is given in table I. The turbulence factor of one wind tunnel was not known and, in this instance, the effective Reynolds number was assumed equal to the test Reynolds number (fig. 2; wings 7, 8, and 9).

DISCUSSION

Effects of Reynolds number on $C_{L_{max}}$.- The data of figure 1 illustrate the importance of Reynolds number on the attainable maximum lift coefficients for similar swept and unswept wings. For the wings shown in figure 1 it appears that the maximum lift coefficients will be higher for the swept wings than for the unswept wings at Reynolds numbers below about 2.0×10^6 and will be lower at higher Reynolds numbers. The data for wings 10 and 11 (fig. 2) show an opposite effect at low Reynolds numbers inasmuch as higher maximum lift coefficients were measured for the unswept wing than for the swept wing at Reynolds numbers of about 1.0×10^6. The data for wings 7, 8, and 9 show higher maximum lift coefficients for the swept wings than for the unswept wing within the range of Reynolds number investigated (between 1.1×10^6 and 4.2×10^6). The swept wings illustrated in figure 1 show a small decrease in $C_{L_{max}}$ with increases in Reynolds number above 4.0×10^6. In the case of wing 3, the decreases in $C_{L_{max}}$ with increases in Reynolds number above 4.0×10^6 may be associated with Mach number effects (Mach numbers above about 0.2).

In each case in which data for comparable swept and unswept wings were available (figs. 1 and 2) a smaller rate of increase of the maximum lift coefficient with Reynolds number was measured for the swept wings than for the unswept wings in the critical range of Reynolds number. For wing 12, an increase in $C_{L_{max}}$ of only about 0.10 was measured for an increase in Reynolds number from 1.7 to 9.3×10^6. Section data showed a similarly small change in $C_{L_{max}}$ with Reynolds number for the NACA 64_1-112 airfoil which is used on wing 12. The differences in the variations of maximum lift coefficient with Reynolds number for wings of approximately similar plan form are attributed to differences in the airfoil section employed, to differences in surface conditions, and to differences in wing-tip shapes. The important effects of airfoil thickness and airfoil camber on the nature of the variations of maximum lift coefficients with Reynolds number are discussed in detail in reference 1. More rapid changes in $C_{L_{max}}$ with Reynolds number, in the critical range of Reynolds number, are shown in reference 1 for thin symmetrical airfoil sections than for airfoil sections of moderate camber and thickness. The effect of increasing the wing-tip thickness and changing the camber of wing 5 on the variation of $C_{L_{max}}$ with Reynolds number for this wing is shown in figure 4. Increasing the wing-tip thickness from 0.15c to 0.18c caused a reduction in $C_{L_{max}}$ but had no appreciable effect on the variation of $C_{L_{max}}$ with Reynolds number except at the highest Reynolds numbers tested. A less pronounced increase in $C_{L_{max}}$ with Reynolds number was measured for the cambered wing than for the two wings with symmetrical sections. The cambered wing section, which is described more fully in reference 8, is considered to give approximately the same characteristics as an NACA 65,3-618 airfoil section with a 0.20c flap deflected -10°.

The variations of $C_{L_{max}}$ with Reynolds number for two wings of approximately triangular plan form are given in figure 3. In both cases, decreases in maximum lift coefficient with Reynolds number were measured.

Effect of sweepback on $C_{L_{max}}$.- The results of systematic tests, made at low Reynolds numbers (below 1.0×10^{6}), of four series of wings of increasing sweepback are given in figure 5(a). The data include tests of both tapered and rectangular wings. Increases in the maximum lift coefficient with increasing angle of sweepback (up to about 50°) were measured for the tapered wings at these low Reynolds numbers. For the rectangular wings, increases in the maximum lift coefficients above those measured for the unswept wings were obtained with increasing angle of sweepback up to 35° for wing series 20-23 and up to 45° for wing series 28-31. Peak values of the maximum lift coefficient were measured at sweepback angles of 10° and 30°, respectively, for wing series 20-23 and 28-31. These results appear to substantiate the results shown in figure 1 in which it may be seen that, at very low values of the Reynolds number, higher values of the maximum lift coefficient were obtained for the tapered swept wings than for the similar tapered unswept wings.

The results of systematic tests made at moderate Reynolds numbers (between 1.1×10^6 and 4.1×10^6) to determine the maximum lift coefficients of tapered wings of increasing sweepback are given in figure 5(b). In this range of Reynolds number, small increases in the angle of sweepback (below about 20°) gave considerably larger increases in $C_{L_{max}}$ than those measured for the approximately similar tapered wings at very low Reynolds numbers (wing series 15–19 of fig. 5(a)). This comparison is made for wings employing different airfoil sections and therefore may not be conclusive. Further increases in the angle of sweepback above 20°, at moderate Reynolds numbers, resulted in appreciable reductions in the maximum lift coefficients attainable (fig. 5(b)). This result is the opposite of that obtained for the tapered wings at very low Reynolds numbers (fig. 5(a)) where appreciable increases in maximum lift coefficient were obtained at high angles of sweepback.

The results of tests to determine the effects of sweepback on $C_{L_{max}}$ at a high value of the Reynolds number (8.2×10^6) is given in figure 5(c). At this high Reynolds number, increasing sweepback caused large reductions in the attainable maximum lift coefficient even for small angles of sweepback. It should be remembered that at moderate and low Reynolds numbers small increases in sweepback resulted in increases in $C_{L_{max}}$.

Effects of various landing aids.– Tests were made of two swept-back wings (wings 3 and 12) to determine the effects of Reynolds number on $C_{L_{max}}$ with and without different landing aids attached to the wings (fig. 6). The addition of a 20-percent-chord 50-percent-span split flap ($\delta_f = 60°$) to wing 12 had little effect on the rate of change of $C_{L_{max}}$ with Reynolds number for Reynolds numbers between 4.25×10^6 and 7.90×10^6. At lower Reynolds numbers (between 1.7×10^6 and 4.25×10^6), however, a more rapid increase in $C_{L_{max}}$ with Reynolds number was measured for the flapped wing than was measured for the unflapped wing.

The addition of leading-edge tip slats to wing 3, as shown in figure 6, had no appreciable effect on the rate of change of $C_{L_{max}}$ with Reynolds number. For wings 3 and 12 small increases in $C_{L_{max}}$ were measured with increasing Reynolds number from 2.0 to about 4.5×10^6; a further increase in Reynolds number to 5.3×10^6 caused a decrease in $C_{L_{max}}$ in both cases. With partial-span split flaps and ailerons deflected and with the slats extended no change in

$C_{L_{max}}$ was measured with increasing Reynolds number from 2.0×10^6 to about 4.5×10^6 for wing 3; increasing the Reynolds number to 5.3×10^6 caused a small decrease in $C_{L_{max}}$. The decrease in $C_{L_{max}}$ due to an increase in Reynolds number from 4.5×10^6 to 5.3×10^6 for wing 3 may be associated with the Mach number effects previously mentioned.

Effects of fuselage.- The variations of $C_{L_{max}}$ with Reynolds number for wings 3 and 12 with and without fuselages are given in figure 7. For wing 12, no appreciable effect on $C_{L_{max}}$ was measured at Reynolds numbers of 2.95×10^6 and 7.95×10^6 as a result of the addition of a fuselage to the wing. The addition of a fuselage to wing 3 caused small reduction in $C_{L_{max}}$ at Reynolds numbers of 2.0×10^6, 2.65×10^6, and 4.65×10^6 but had no effect on $C_{L_{max}}$ at Reynolds numbers of 3.3×10^6 and 4.0×10^6.

SUMMARY OF RESULTS

An analysis of available foreign and American data relating to Reynolds number effects on the maximum lift coefficients of swept-back wings showed the following results:

1. At low Reynolds numbers (below about 2.0×10^6) higher maximum lift coefficients were measured in most cases for moderately swept-back wings than for unswept wings of similar plan form; at high Reynolds numbers, however, increasing sweepback resulted in decreasing maximum lift coefficients.

2. A smaller rate of increase of the maximum lift coefficient with Reynolds number was measured for the swept-back wings than for similar unswept wings in the critical range of Reynolds number.

3. Decreases in the maximum lift coefficient with increasing Reynolds number were measured for two wings of approximately triangular plan form.

4. The addition of fuselages to two swept-back wings had little effect on the variations of maximum lift coefficient with Reynolds number for these wings. Similar results were obtained when various landing aids such as split flaps were installed on

the same two swept-back wings and when leading-edge tip slats were installed on one of the two swept-back wings.

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TABLE I.– TURBULENCE FACTORS FOR

WIND TUNNELS

Wind tunnel	Turbulence factor
T. H. Hannover 1.5 meter	1.17
DVL 5 by 7 meter	1.04
Chalais Meudon 8 by 16 meter	1.43
United Aircraft Corporation 18-foot	1.00
LMAL 19-foot Pressure	1.00
RAE High Speed	1.00 (assumed)
DVL 2.15 by 3 meter	1.03
LMAL Full Scale	1.10
LMAL $\frac{1}{15}$-scale model full scale	1.20
AVA 1.25 meter	1.37
Braunschweig 1.2 meter	1.19
LMAL VDT	2.60

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Wing	Λ, deg	A	c_t/c_r	Airfoil section	Source of data
1	37.0	5.7	0.54	root 0012-64 tip 0010-64	T.H. Hannover 1.5 meter tunnel, Ref. 2
1	37.0	5.7	.54	root 0012-64 tip 0010-64	D.V.L. 5 by 7 meter tunnel, Ref. 3
1	37.0	5.7	.54	root 0012-64 tip 0010-64	Chalais Meudon 8 by 16 meter tunnel, Ref. 4
2	0.25c unswept	5.7	.54	root 0012-64 tip 0010-64	T.H. Hannover 1.5 meter tunnel, Ref. 2
2	0.25c unswept	5.7	.54	root 0012-64 tip 0010-64	D.V.L. 5 by 7 meter tunnel, Ref. 3
3	a 38.2	4.7	.42	root 65[illegible]-114 a=.6 tip 65,2-212 a=.6	United Aircraft Corp. 18 foot tunnel Unpublished data
4	a 0.30c unswept	5.3	.50	root 65[illegible]-114 a=.6 tip 65,2-212 a=.6	United Aircraft Corp. 18 foot tunnel Unpublished data

a Airfoil sections normal to 0.30c line.

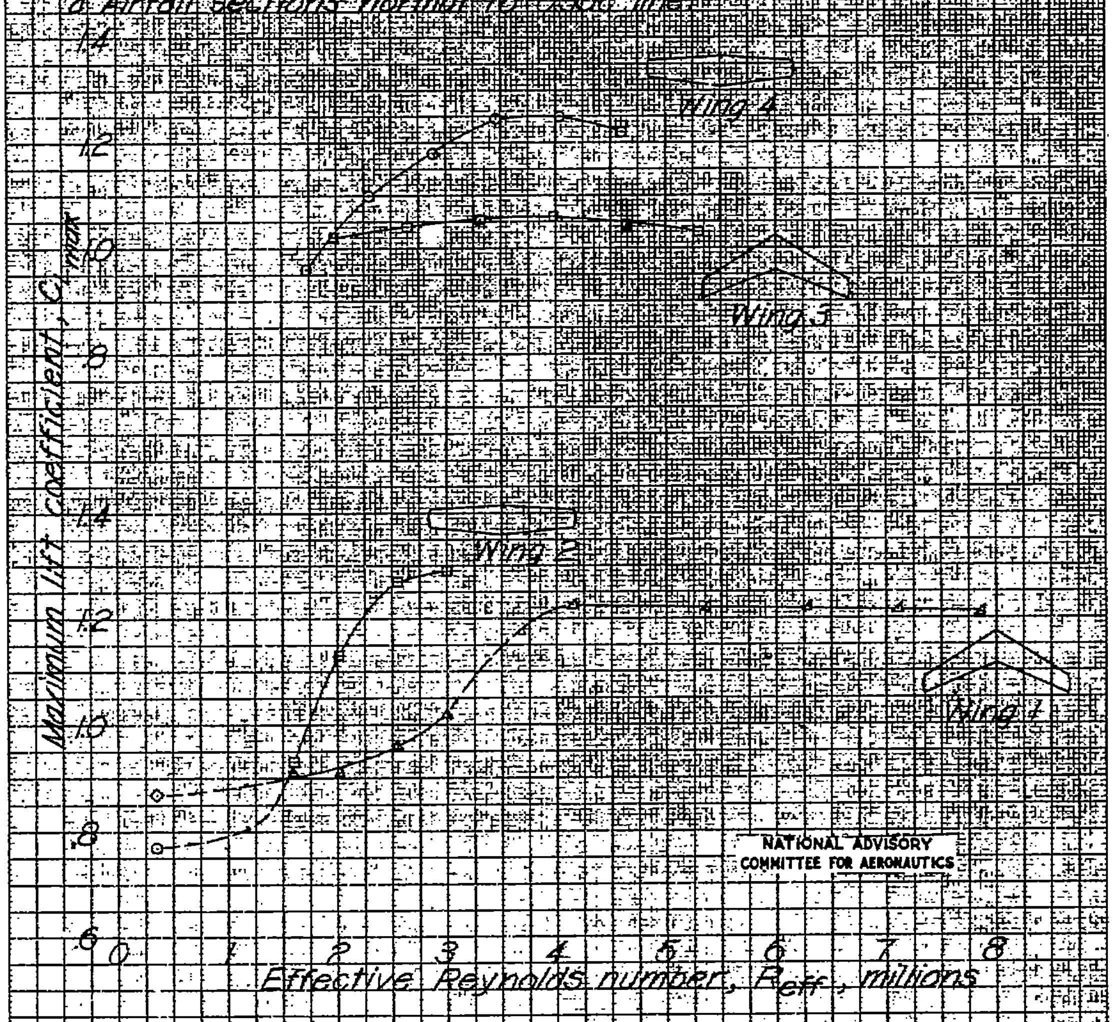

Figure 1.- Effects of Reynolds number on the $C_{L_{max}}$ of similar swept and unswept wings.

Wing	Λ, deg	A	c_t/c_r	Airfoil section	Source of data
5	25.8	7.4	0.25	root 65(318)-019, tip 65(318)-015	LMAL 19-foot pressure tunnel, Unpublished data.
6	0.25c unswept	7.4	.25	root 65(318)-019, tip 65(318)-015	LMAL 19-foot pressure tunnel, Unpublished data.
7	0.25c unswept	5.8	.57	root, tip } sym. 0.14c thick	RAE High speed tunnel, Ref. 5.
8	36.6	5.8	.57	root, tip } sym. 0.14c thick	RAE High speed tunnel, Ref. 5
9	22.1	5.8	.57	root, tip } sym. 0.14c thick	RAE High speed tunnel, Ref. 5
10	37.5	5.0	.50	root, tip } 0012	DVL 2.15 by 3 meter tunnel, Ref. 6
11	0.25c unswept	5.0	.50	root, tip } 0012	DVL 2.15 by 3 meter tunnel, Ref. 6

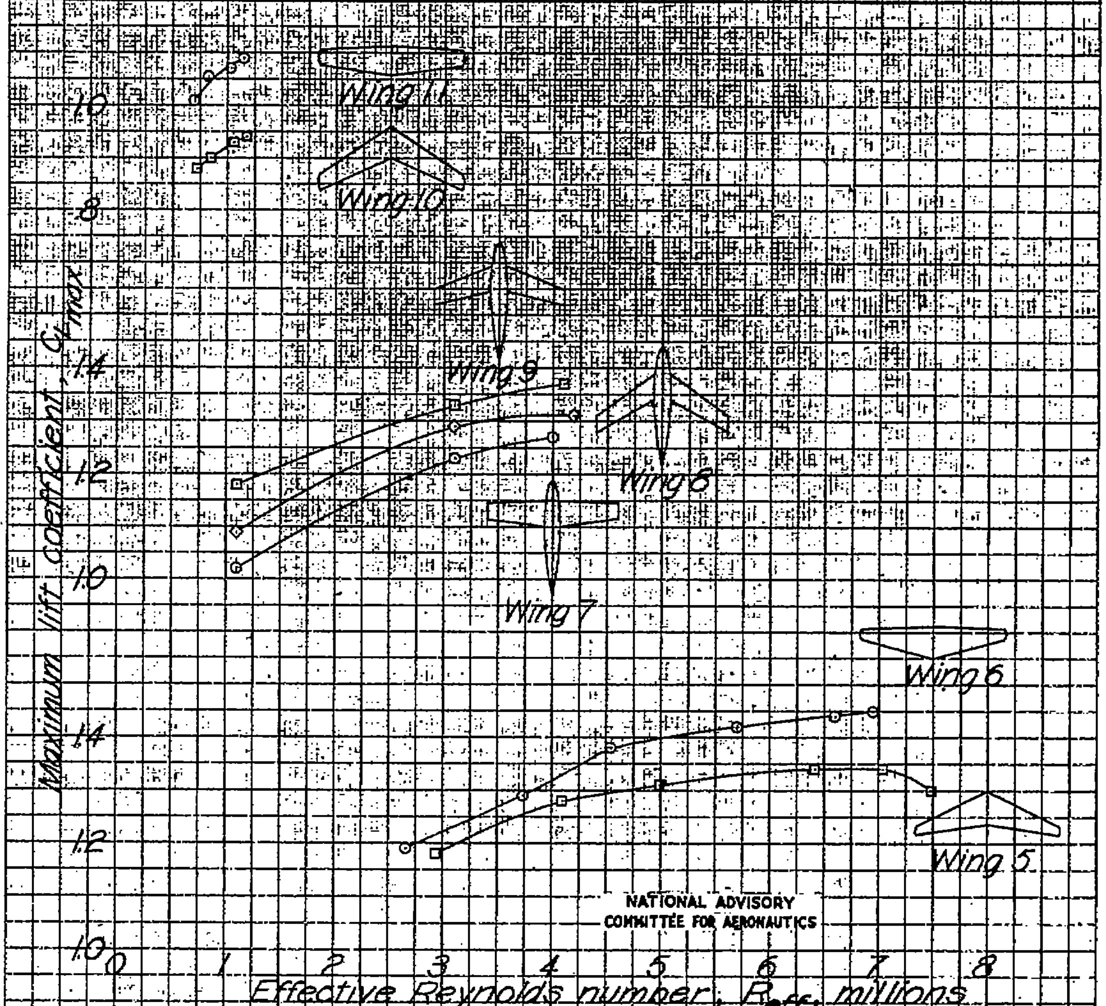

Figure 2.- Effects of Reynolds number on the $C_{L_{max}}$ of similar swept and unswept wings.

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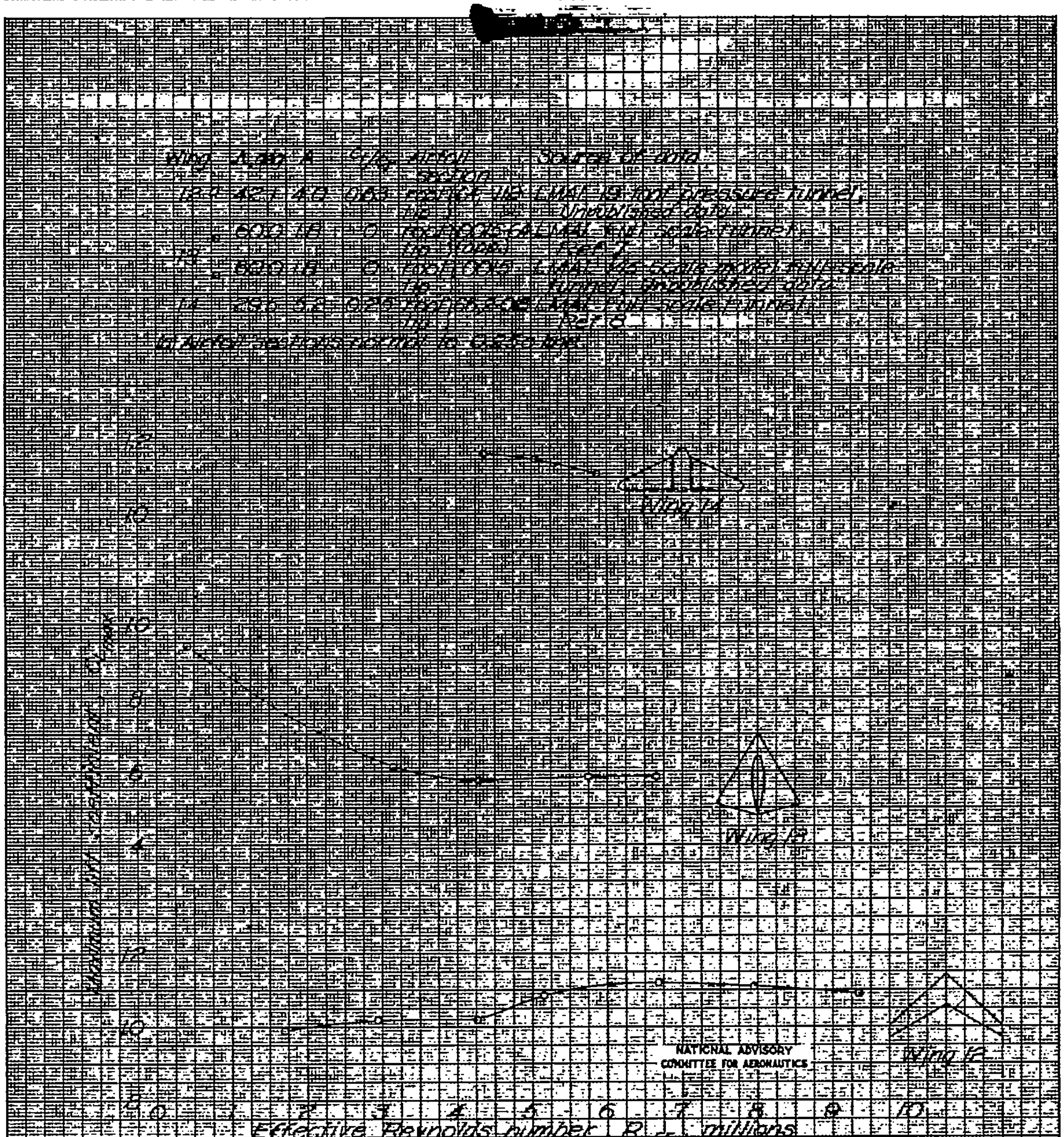

Figure 3.- Effects of Reynolds number on the $C_{L_{max}}$ of swept wings with widely different planforms.

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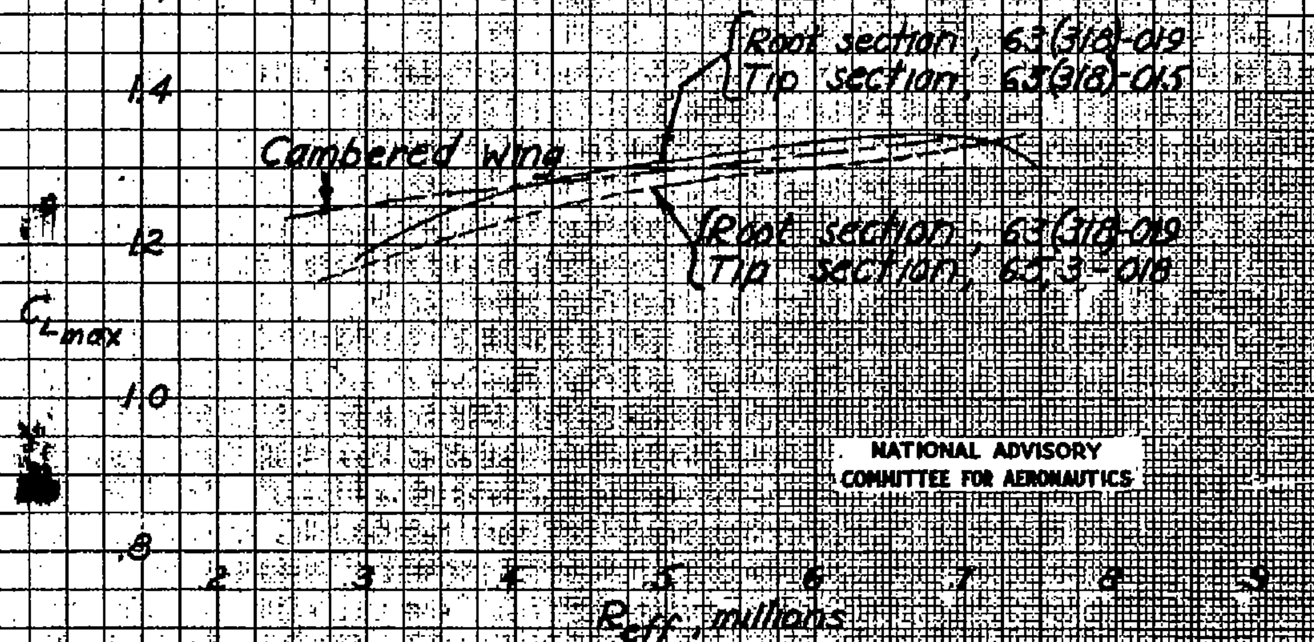

Figure 4.- Effect of changes in wing-tip thickness and wing camber on the variation of $C_{L_{max}}$ with Reynolds number for wing 5. Data from reference 9 and figure 2.

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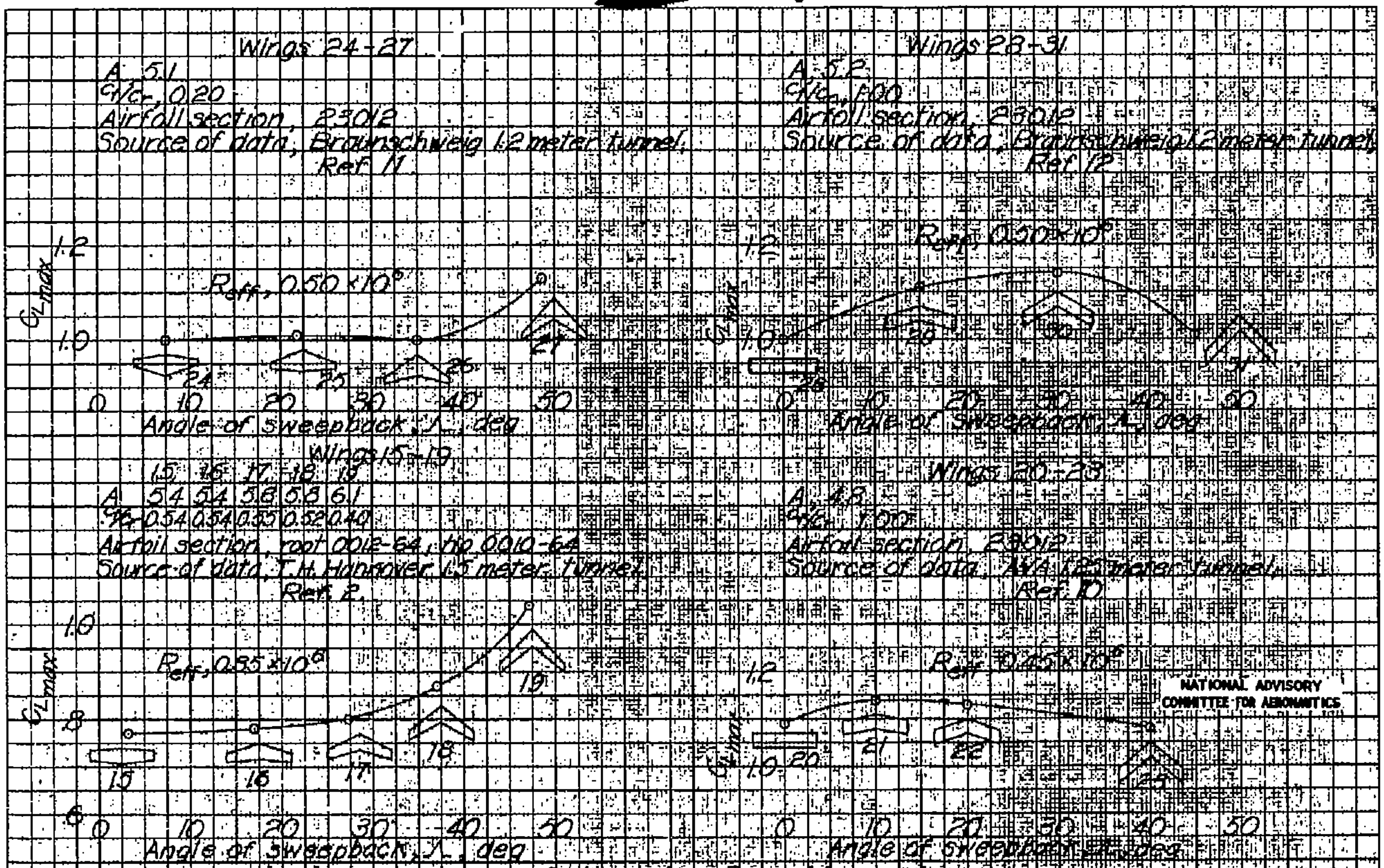

(a) Data at low Reynolds numbers.

Figure 5.- Effect of sweepback on maximum lift coefficient for different Reynolds numbers.

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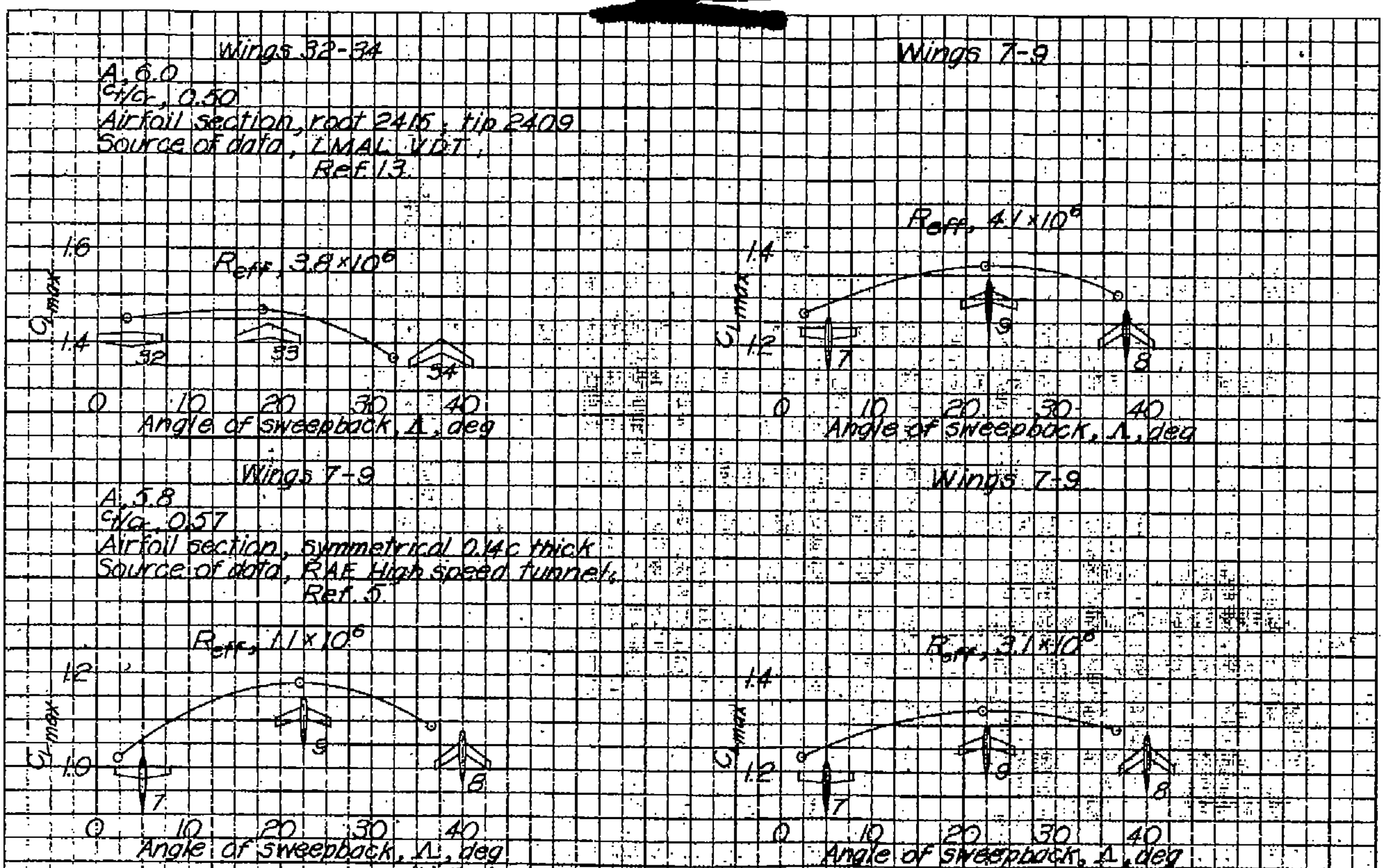

(b) Data at moderate Reynolds numbers

Figure 5 - Continued

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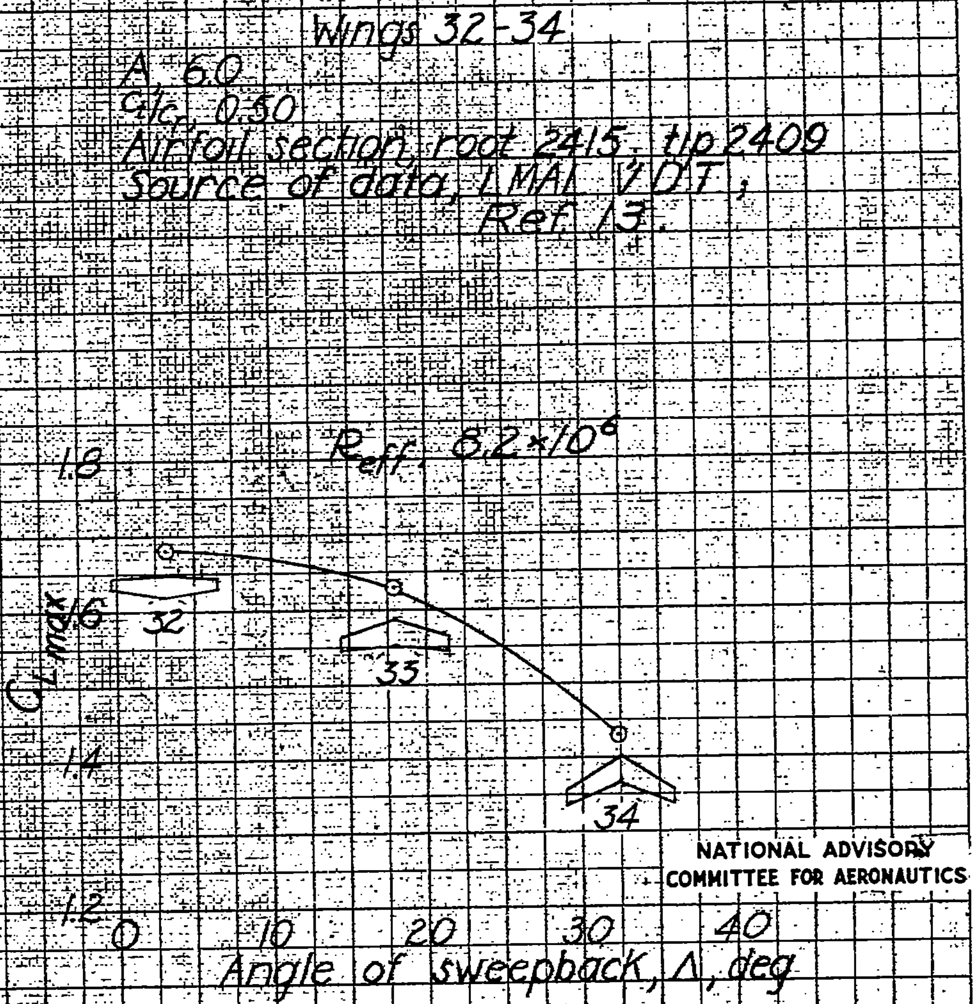

(c) Data at high Reynolds numbers

Figure 5.- Concluded.

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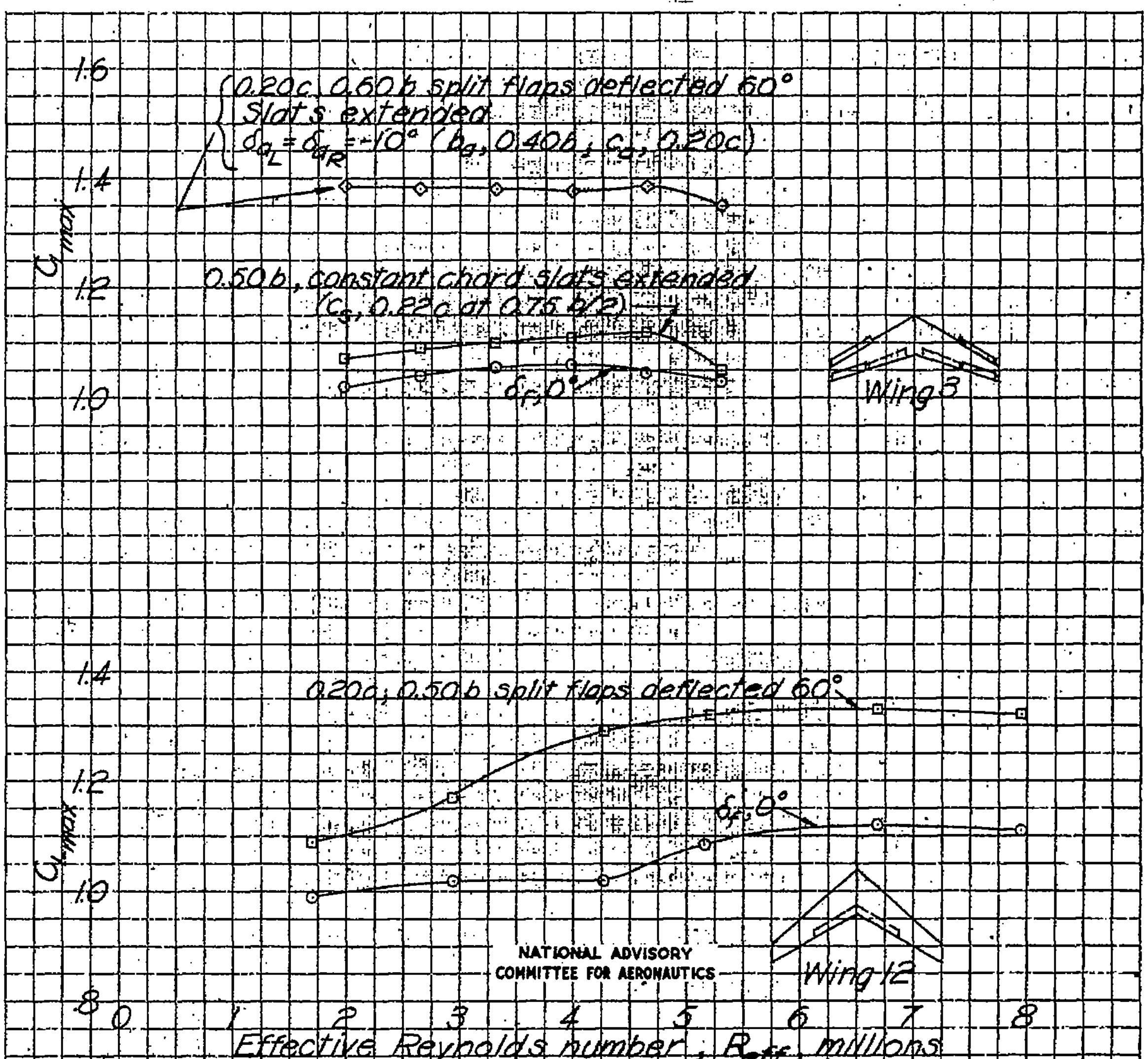

Figure 6.- Effects on the variation of $C_{L_{max}}$ with Reynolds number of the installation of various landing aids to swept wings.

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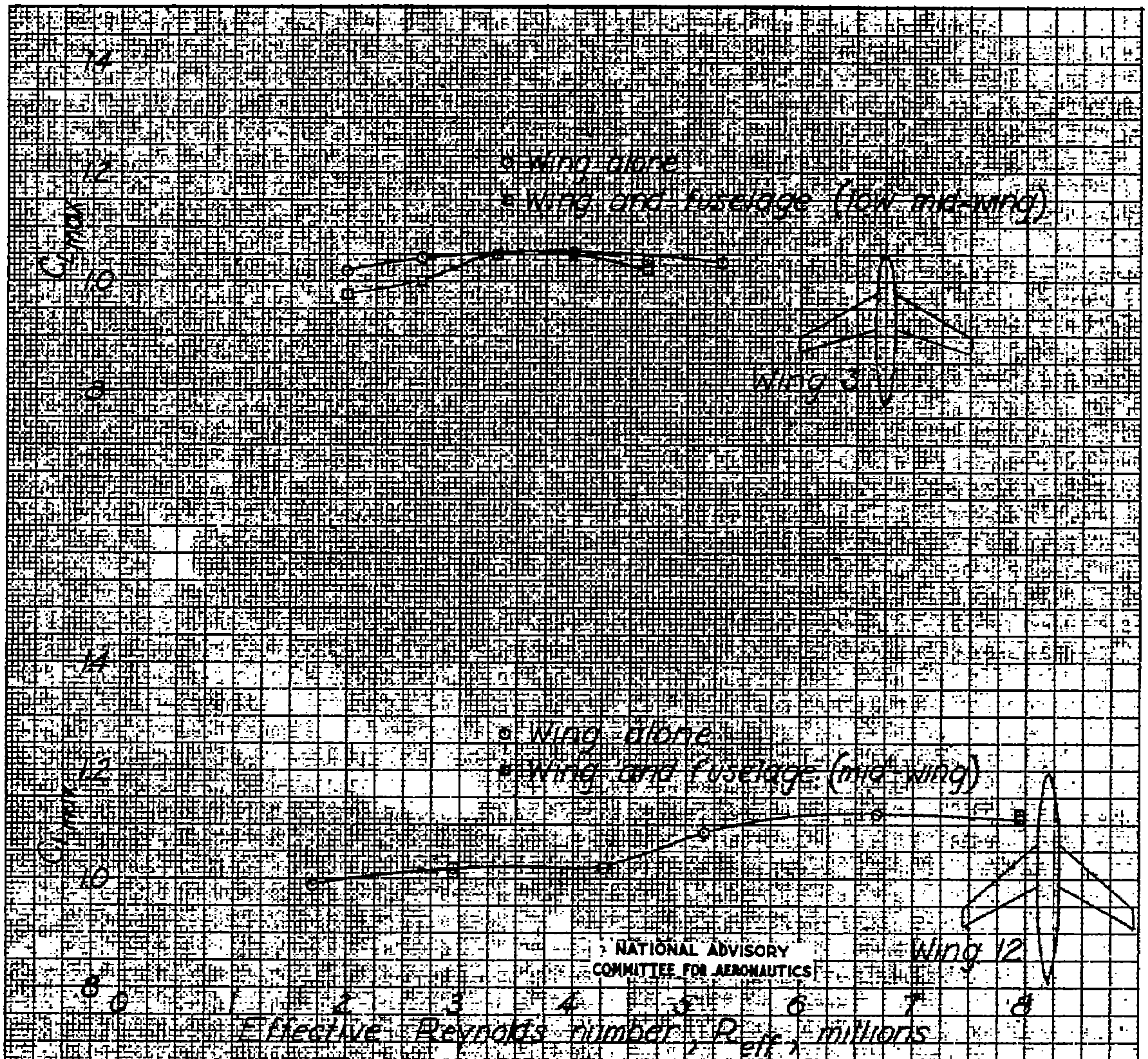

Figure 7.- Effects on the variation of $C_{L_{max}}$ with Reynolds number of the addition of fuselages to swept wings.

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